Probing the Early Universe with the SZ Effect

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The Cosmic Microwave Background Radiation (CMBR) which we observe today is relic radiation which last interacted with matter more than 10 billion years ago, when the expanding universe cooled to the point that free electrons and ionized nuclei recombined to form atoms. Prior to recombination, scattering between photons and free electrons was a very frequent occurrence, and the distance light could penetrate was small; afterwards, with free electrons out of circulation, the universe became largely transparent to light. Thus, the CMBR photons we observe today give us a clear view of the state of the early universe. Measured deviations in the intensity of the CMBR trace the small perturbations in the primordial matter density, which have been amplified by gravitational forces to form the magnificent, complex structures which comprise the present-day universe.

In certain massive objects, however, interactions between CMBR photons and free electrons continue to play an important cosmological role. The largest gravitationally collapsed structures in the universe are clusters of galaxies, which have masses up to 100,000 times greater than the mass of our galaxy. At optical wavelengths, clusters are beautiful objects consisting of thousands of galaxies, each containing billions of stars, all bound together by a strong gravitational field. The galaxies and stars, however, only account for a few percent of the total mass. Most of the 'normal' (baryonic) matter resides in the hot gas ($T\sim100$ million degrees Kelvin) which permeates the galaxy cluster. When CMBR photons interact with the free electrons in this ionized gas, a unique feature -- the Sunyaev-Zel'dovich (SZ) Effect -- is imprinted on the spectrum of the microwave background, which proves to be of fundamental importance for cosmology.

The interaction of a CMBR photon with a hot cluster electron will, on average, cause the photon to gain a small amount of energy. Even though there is a tremendous amount of gas contained in a cluster of galaxies ($\sim 10^{13}$ times the mass of our Sun), the probability that a CMBR photon will interact with any of the electrons in the cluster gas is small. The SZ Effect is therefore subtle, changing the brightness of 2.73~K CMBR blackbody spectrum by at most 0.1\%. This spectral distortion has a distinct signature: in the low frequency part of the CMBR spectrum, the SZ scattering process causes the brightness of the CMBR to be diminished towards galaxy clusters, producing 'holes' in the background radiation field (Fig. 1). The scattered photons are shifted to higher energies, producing an excess in the high frequency part of the CMBR spectrum. When the SZ Effect was first proposed 30 years ago \citep{sunyaev70,sunyaev72}, it proved to be exceptionally difficult to detect; accurate measurements are now possible using experimental techniques developed over the last decade \citep{birkinshaw99,carlstrom00}.

The SZ Effect has been used so far to independently determine the expansion rate of the universe, Hubble's constant, and the matter density of the universe, Ω_M. The ability to determine these important cosmological quantities rests on the fact that the magnitude of the SZ Effect is proportional to the total number of free electrons contained in the cluster, weighted by their temperature. An accurate measure of the SZ Effect thus leads to an estimate of the cluster gas mass, provided that the gas temperature is known. The gas temperature is obtained using space-based observatories to measure the spectrum of the copious x-ray emission from the hot gas. The x-ray temperature is also used to determine the depth of the gravitational potential well, which yields the total mass required to bind the cluster together. It is then possible to determine the fraction of normal matter to total matter contained within galaxy clusters; this fraction is significant because the composition of objects as large and massive as galaxy clusters should reflect the composition of the universe as a whole. Finally, the total matter density of the universe is obtained by scaling the measured baryon density of the universe \citep{burles99} by the baryon fraction derived from SZ Effect measurements. Like other recent techniques, the SZ Effect observations indicate that the mass density of the universe, including the mysterious dark matter, is quite low: $\Omega_M \sim 0.25$ \citep{myers97,grego01}. The measured mass density is insufficient to account for a flat universe, which is strongly indicated by recent CMBR anisotropy measurements \citep{miller99,debernardis00,hanany00}. Apparently, roughly three fourths of the present energy density in the universe is in some yet undiscovered form.

The expansion rate of the universe, Hubble's constant, is also determined by combining SZ Effect and x-ray measurements. The strength of the x-ray emission is proportional on the square of the gas density, in contrast to the SZ Effect, which is linearly proportional to the gas density. A combination of the two measurements allow the gas density and cluster distance to be determined; a direct measurement of Hubble's constant is then obtained by folding in the cluster's recessional velocity. Strong constraints on the cosmic distance scale will require SZ Effect and X-ray observations of a large sample of galaxy clusters, which are currently underway \citep{birkinshaw99,reese00,carlstrom00,mason01,saunders01}.

A remarkable property of the SZ Effect is that its brightness depends only on the properties of the cluster gas -- unlike most emission mechanisms, the brightness of the SZ Effect does not depend on cluster distance. It will soon be possible to exploit this powerful and unusual property to explore the distant universe. Specifically, the SZ Effect will be used to determine the abundance and evolution of massive galaxy clusters from the epoch of their formation to the present. Figure 2 shows that the number density of massive clusters is a strong indicator of the cosmological parameters of the universe, and also demonstrates that a large area interferometric SZ Effect survey will be able to detect massive galaxy clusters at whatever epoch they have formed \citep{holder00,haiman01}. Present theories, which assume that the initial spectrum of density fluctuations have a normal (Gaussian) distribution, predict that massive clusters should not have formed at redshifts $z \gtrsim 3$, but this has not yet been confirmed experimentally ($1+z$ is the factor by which the universe has expanded since the photon was emitted). If, in fact, large non-Gaussian fluctuations existed in the early universe, then clusters will have formed at earlier epochs than those currently predicted. Because the SZ Effect is independent of distance, results of these surveys will provide an incisive test of theories of the structure and evolution of the universe, as well as an independent determination of fundamental cosmological parameters.